Relativistic Heavy Ion Collider Operations and Performance Evolution

RHIC overview

Luminosity and polarization evolution

Performance limitations

RHIC II luminosity upgrade

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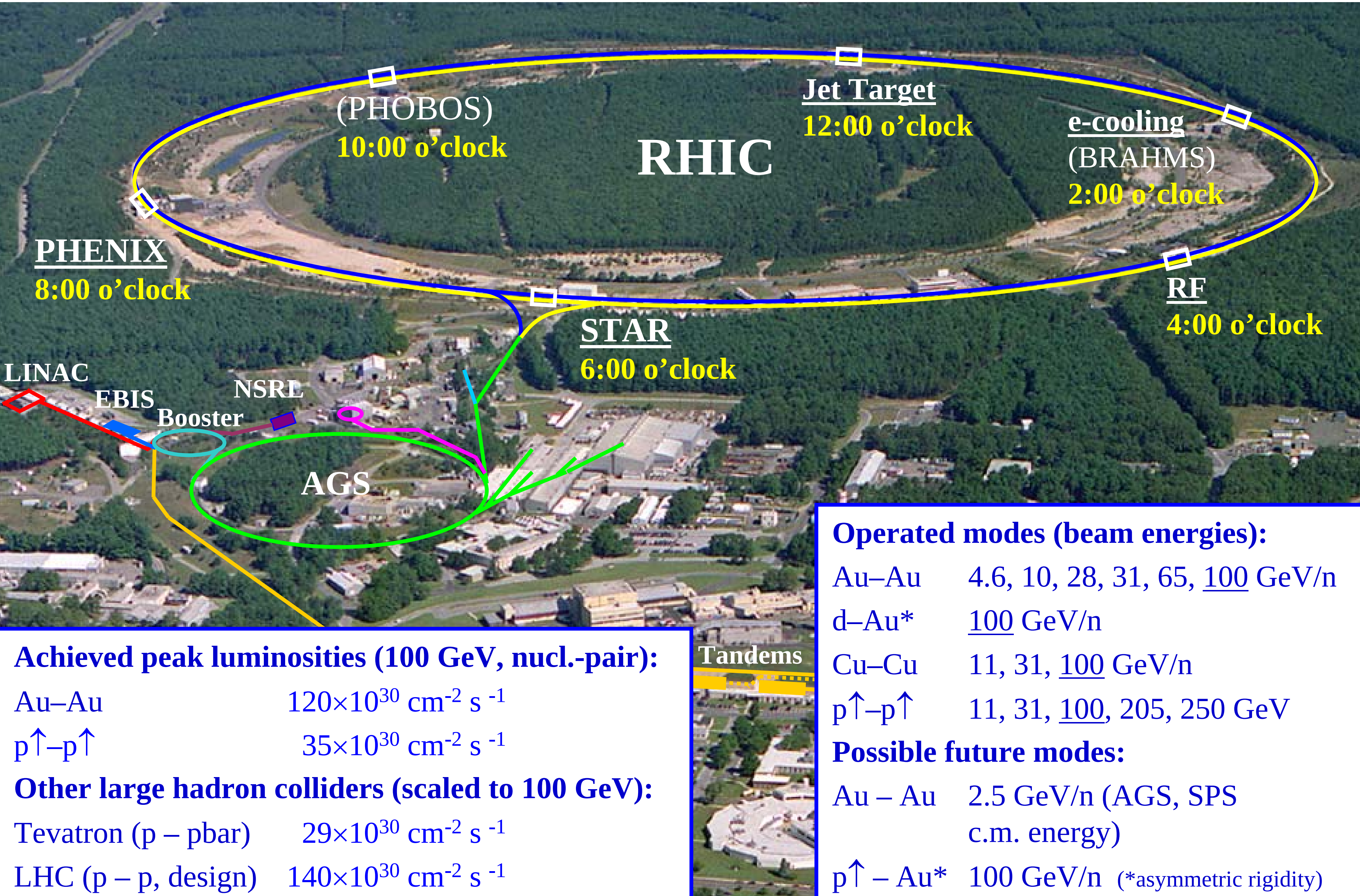
Thomas Roser
RHIC S&T Review
July 18, 2007

RHIC – a High Luminosity (Polarized) Hadron Collider



Achieved peak luminosities (100 GeV, nucl.-pair):

Au–Au	120×10^{30} cm^{-2} s^{-1}
p↑–p↑	35×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 100 GeV):

Tevatron (p – pbar)	29×10^{30} cm^{-2} s^{-1}
LHC (p – p, design)	140×10^{30} cm^{-2} s^{-1}

Operated modes (beam energies):

Au–Au	4.6, 10, 28, 31, 65, <u>100</u> GeV/n
d–Au*	<u>100</u> GeV/n
Cu–Cu	11, 31, <u>100</u> GeV/n
p↑–p↑	11, 31, <u>100</u>, 205, 250 GeV

Possible future modes:

Au – Au	2.5 GeV/n (AGS, SPS c.m. energy)
p↑ – Au*	100 GeV/n (*asymmetric rigidity)

RHIC Design and Achieved Parameters

Mode	No of bunches	Ions/bunch $[10^9]$	β^* [m]	Beam pol.	$L_{store\ ave}$ $[cm^{-2}s^{-1}]$	$A_1A_2L_{store\ ave}$ $[cm^{-2}s^{-1}]$	$A_1A_2L_{peak}$ $[cm^{-2}s^{-1}]$
				Design values (1999)			
Au – Au	56	1.0	2		2×10^{26}	8×10^{30}	31×10^{30}
p – p	56	100	2		4×10^{30}	4×10^{30}	5×10^{30}
				Achieved values			
Au – Au	103	1.1	0.8		12×10^{26}	46×10^{30}	120×10^{30}
d – Au	55	120/0.7	2		2×10^{28}	8×10^{30}	28×10^{30}
Cu – Cu	37	4.5	0.9		80×10^{26}	32×10^{30}	79×10^{30}
p↑ – p↑	111	130	1	65%	20×10^{30}	20×10^{30}	35×10^{30}
				Enhance design values (2009)			
Au – Au	111	1.1	0.9		8×10^{26}	31×10^{30}	155×10^{30}
p↑ – p↑	111	200	0.9	70%	60×10^{30}	60×10^{30}	90×10^{30}

<u>Nucleon-pair luminosity</u>: luminosity calculated with nucleons of nuclei treated independently; allows comparison of luminosities of different species; appropriate quantity for comparison runs.

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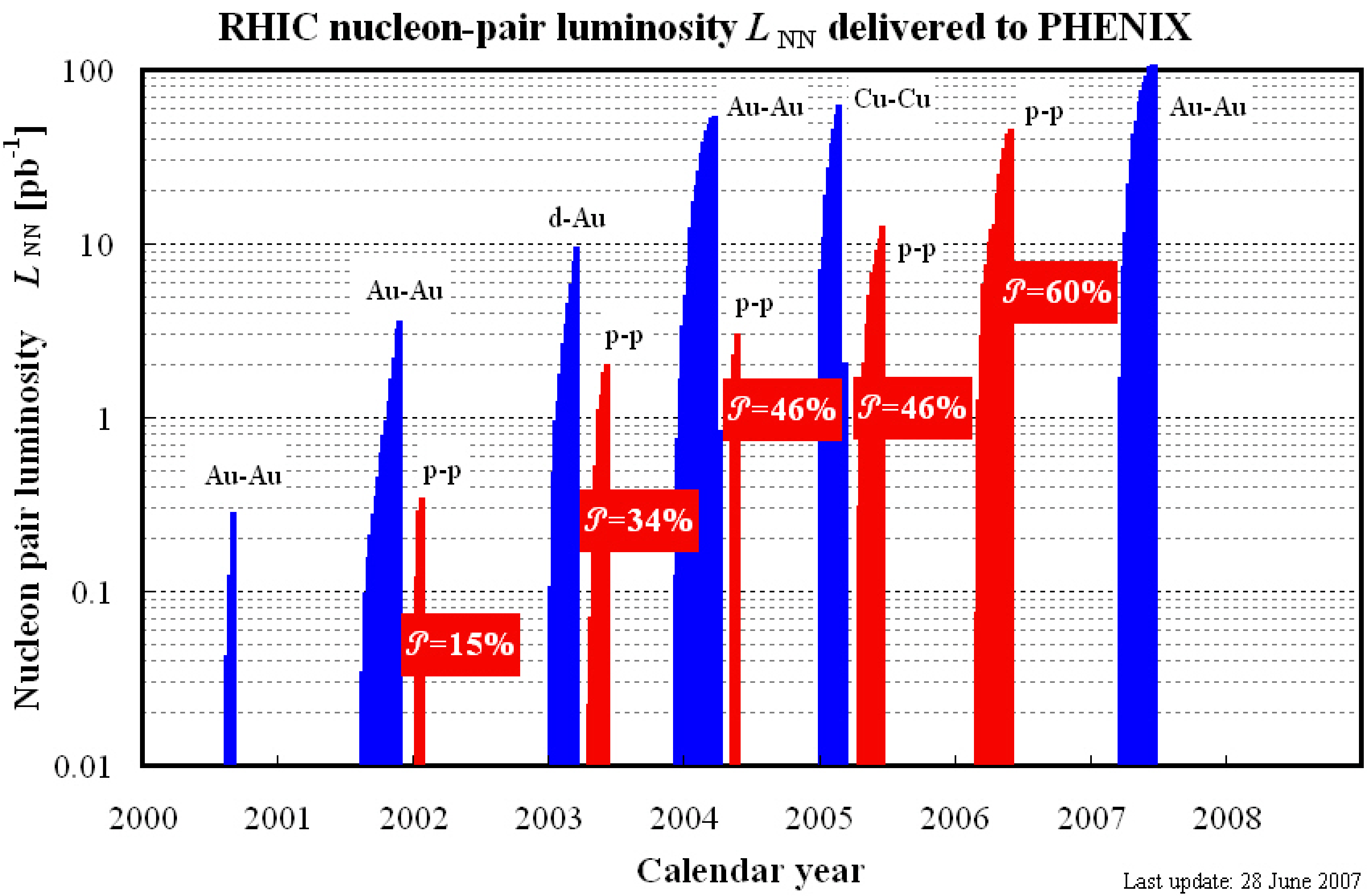
Delivered Luminosity and Polarization



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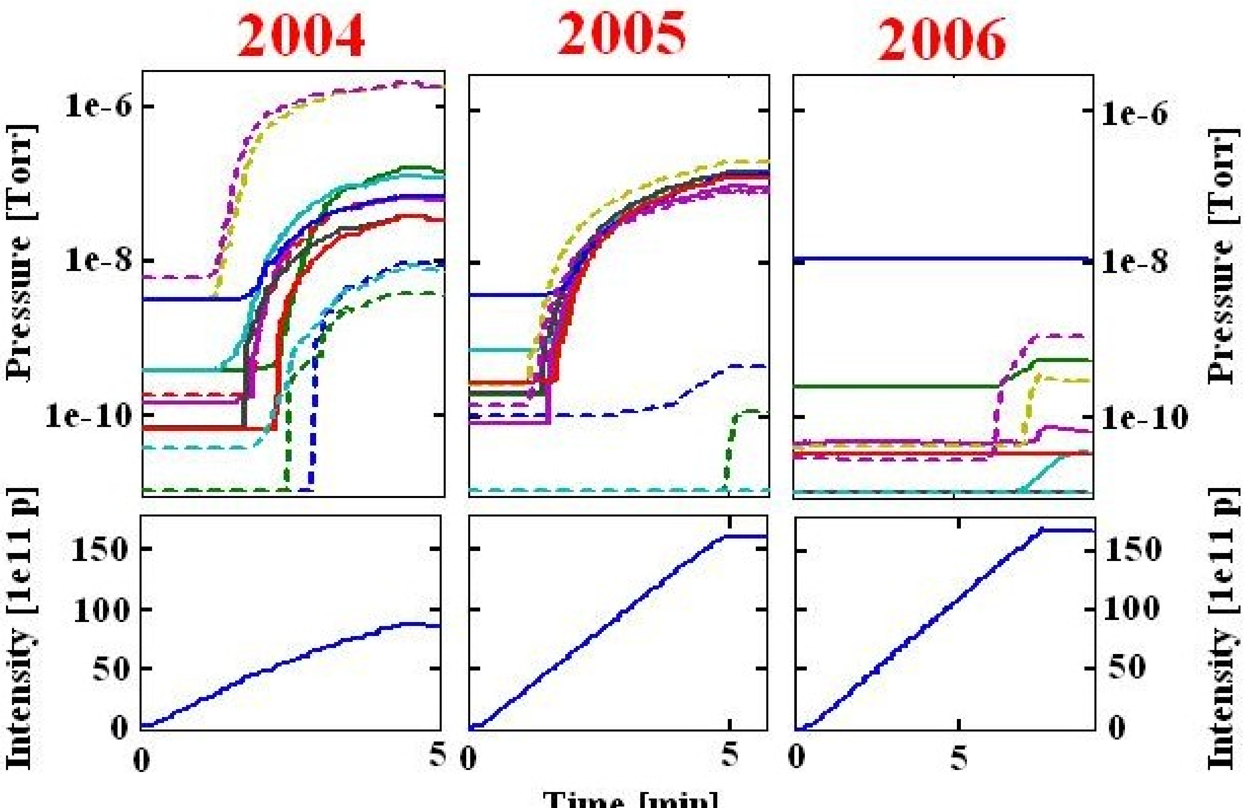
Luminosity Limit: Dynamic Pressure Rise



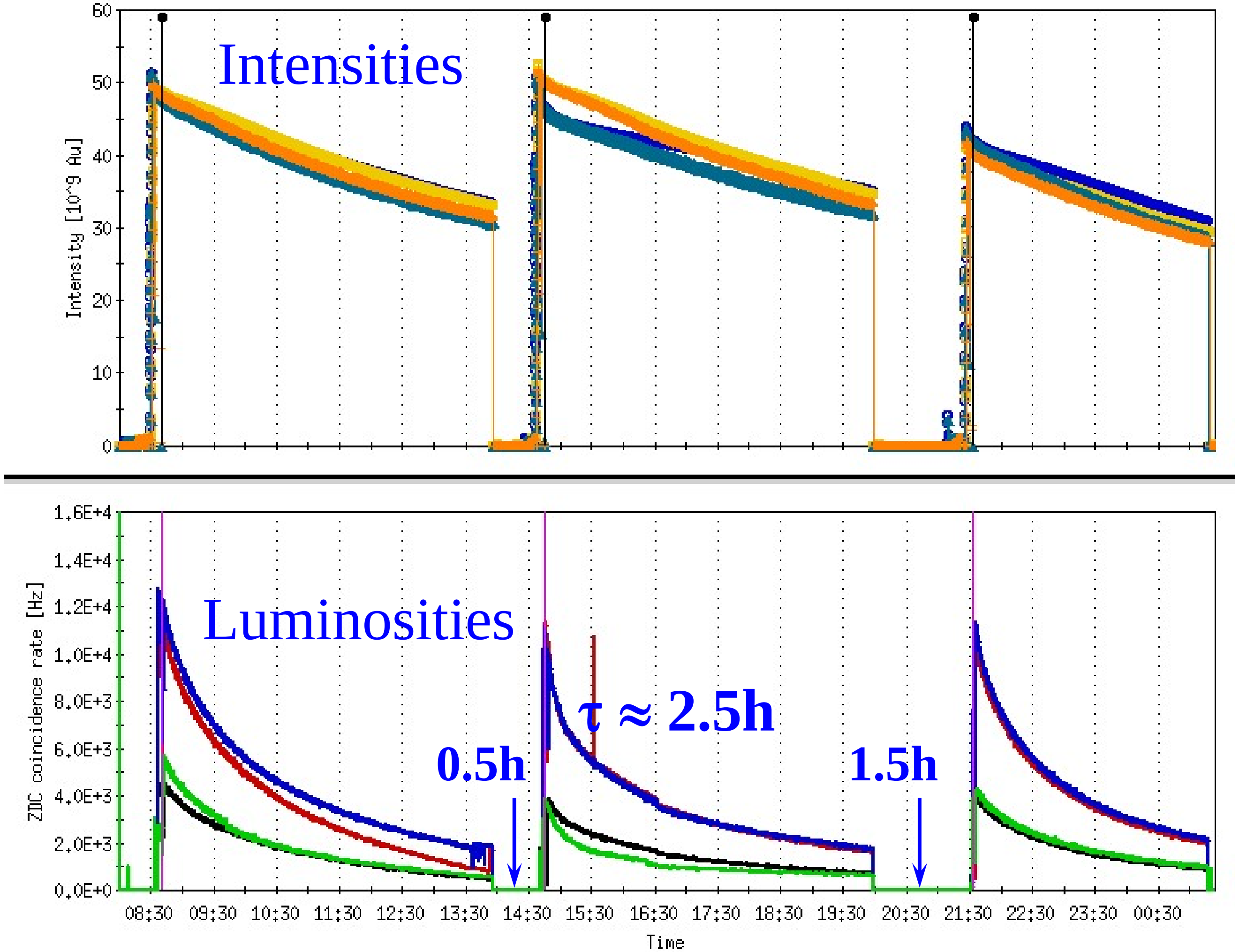
Dynamic pressure rise caused by electron clouds

Upgraded warm and cold vacuum system:

- installed 430m of NEG-coated pipes (~700m warm sections)
- reduced pressure in cold section to 10^{-7} Torr before cool-down

Dynamic pressure currently not a concern during operation

Luminosity Limit – Intra-Beam Scattering (IBS)

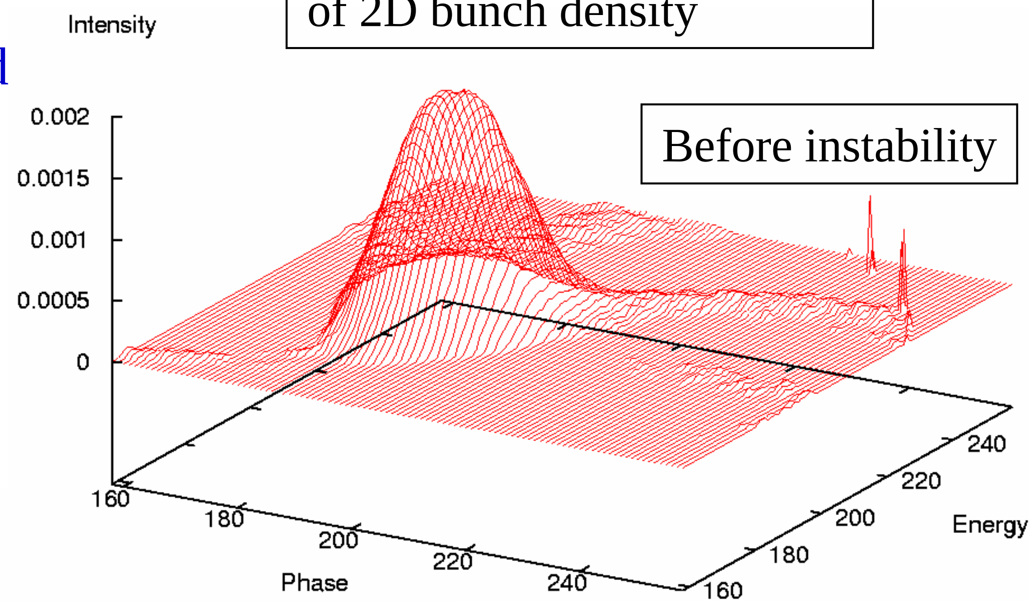


- Debunching requires continuous gap cleaning
- Luminosity lifetime requires frequent refills
- Ultimately need cooling at full energy

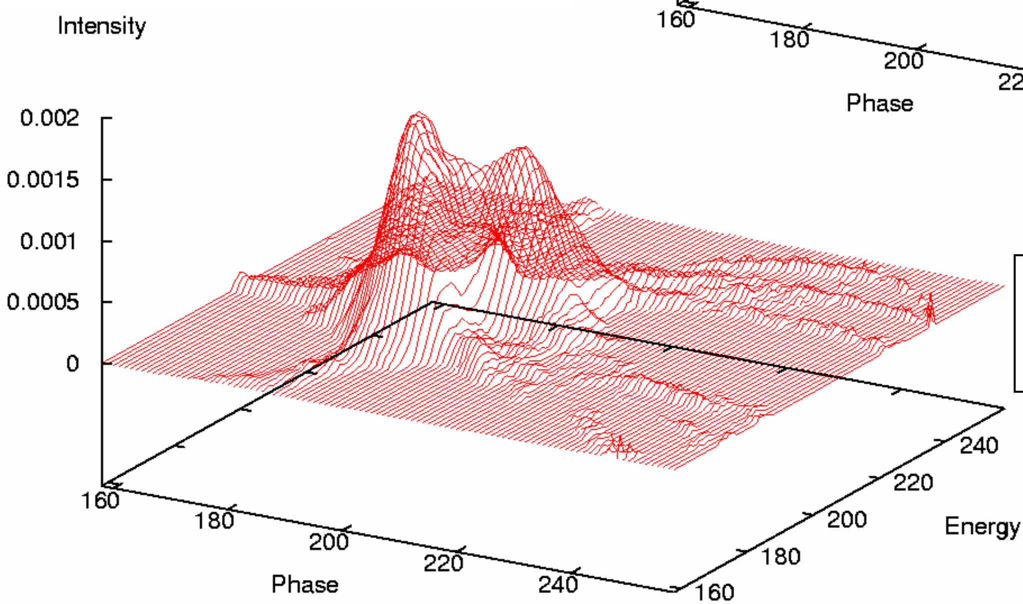
Luminosity Limit – Fast Instability Near Transition

- Fast transverse instability (~ GHz)
- High sensitivity around transition
- Effect of broadband impedance and electron clouds
- Cures: beam-beam tune spread, octupoles, adjust crossing of zero-chromaticity, suppress electron clouds, chromaticity jump

Tomographic reconstruction of 2D bunch density



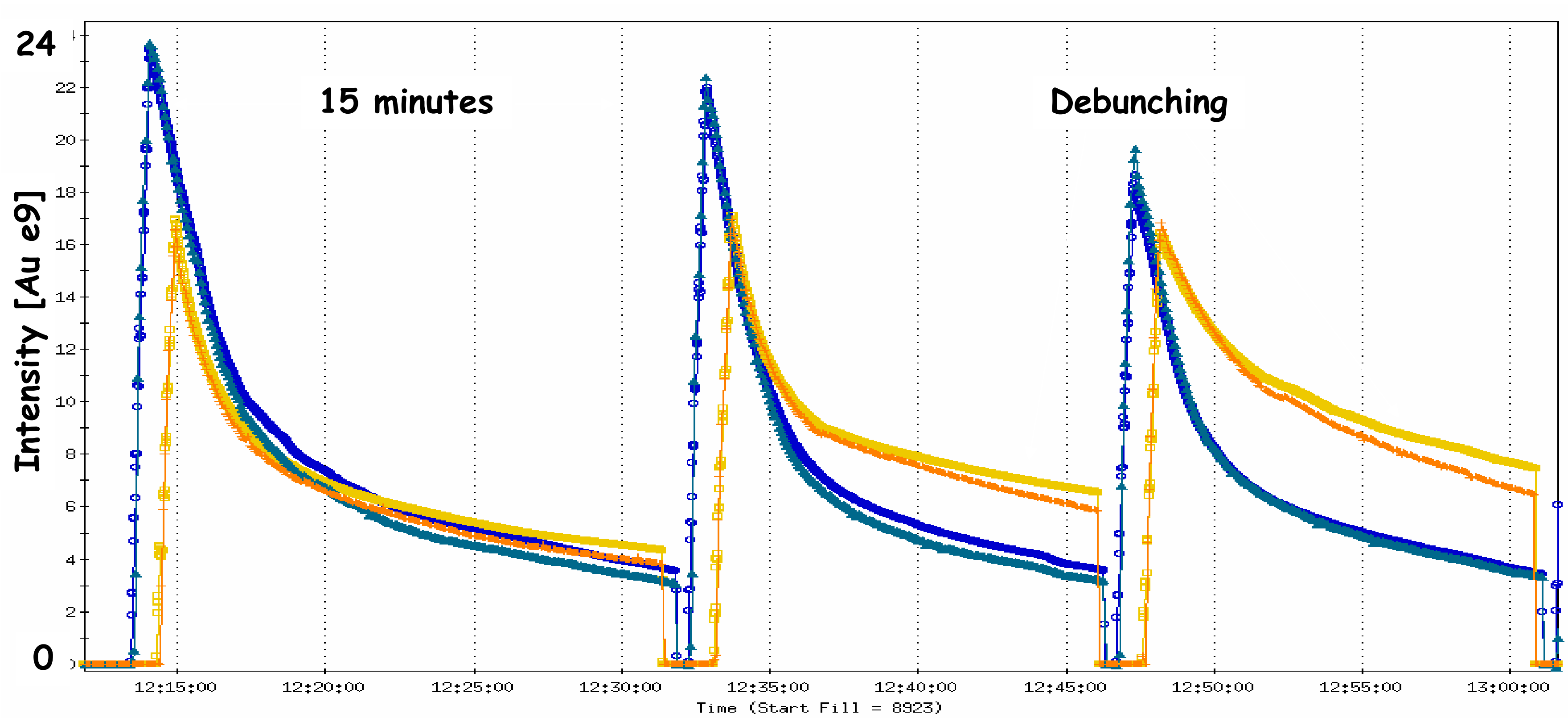
Before instability



After instability with ~ 10 ms growth rate

Low energy Au-Au operation (1)

Demonstrated Au-Au collisions at $\sqrt{s}$ = 9.2 GeV/nucleon (T. Satogata et al.)
Luminosity not yet analyzed quantitatively.



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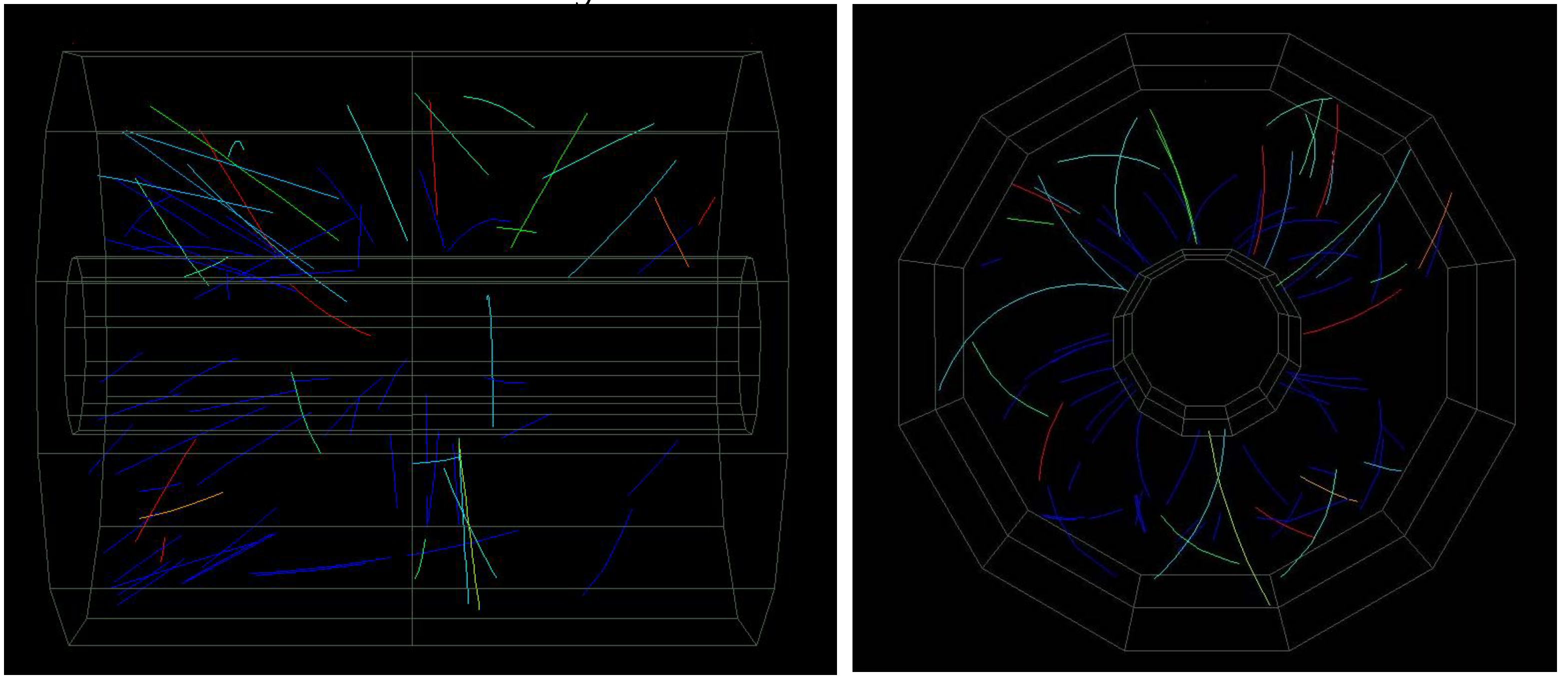
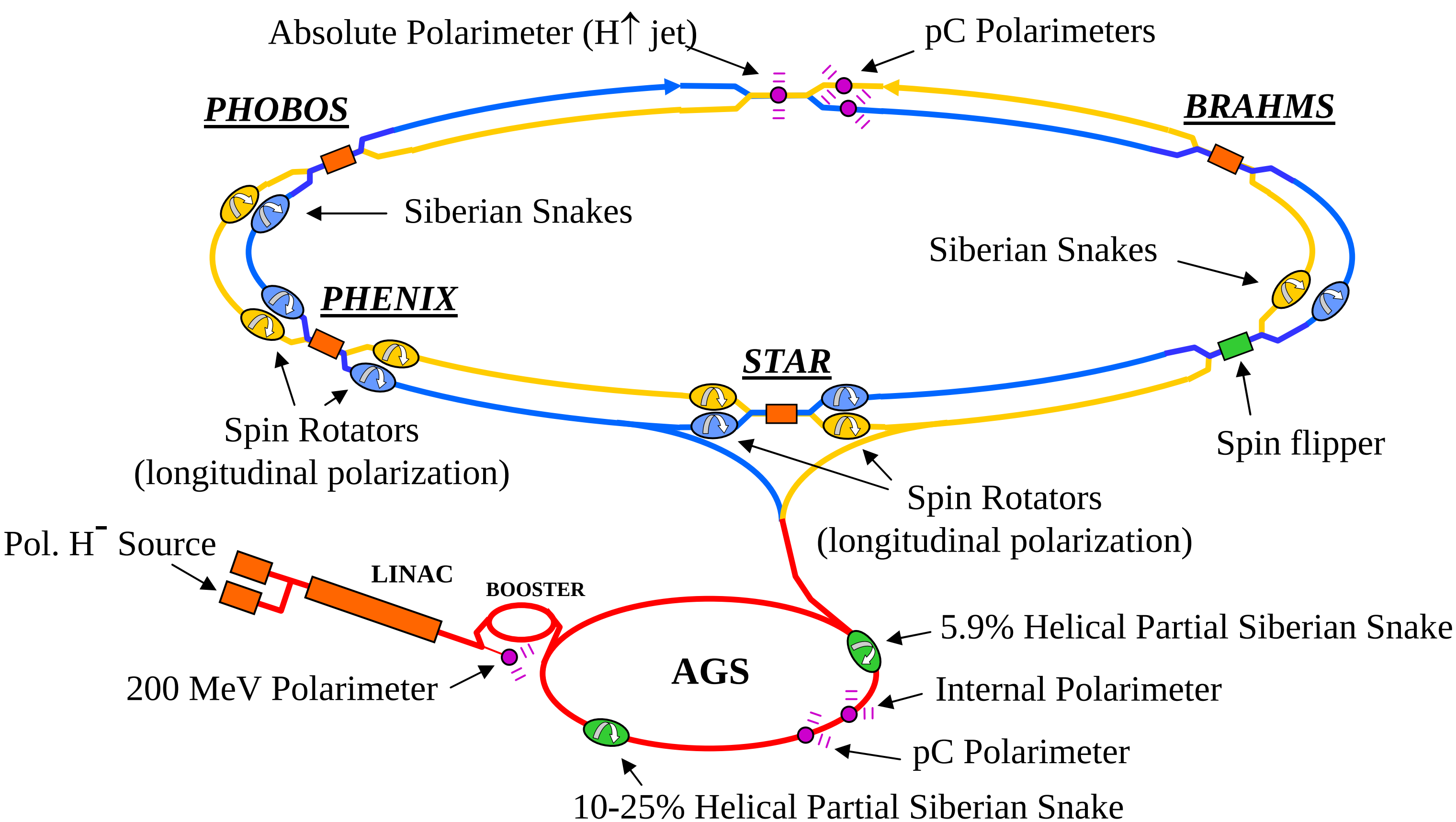
Low energy Au-Au operation (2)

Event seen by the STAR detector.



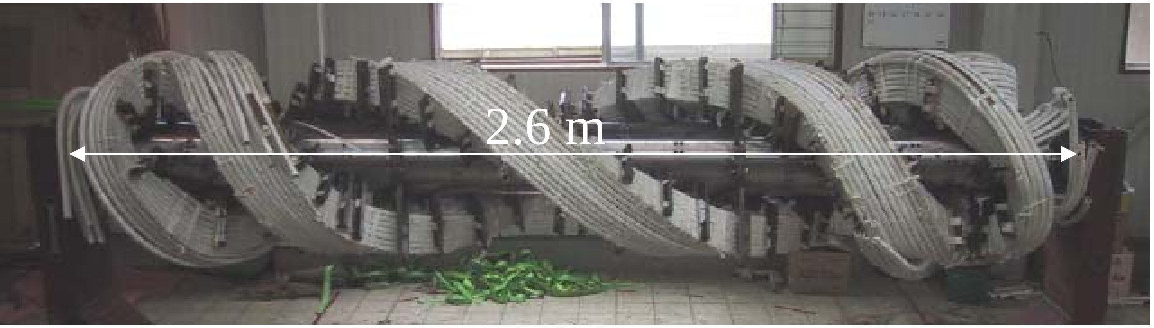
- Low energy operation in principle possible. (1/2 normal injection energy)
- e-cooling in AGS for luminosity increase at even lower energies (down to 1/4 or normal injection).

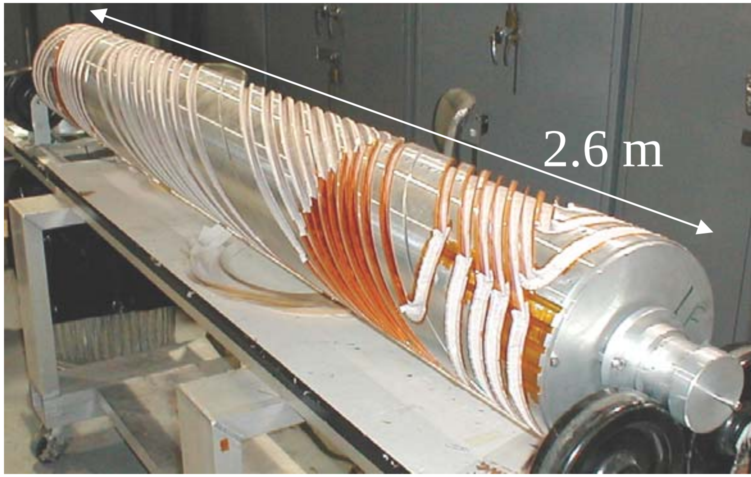
RHIC – First Polarized Hadron Collider



Without Siberian snakes: $\nu_{sp} = G\gamma = 1.79$ E/m → ~1000 depolarizing resonances
With Siberian snakes (local 180° spin rotators): $\nu_{sp} = ½$ → no first order resonances
Two partial Siberian snakes (11° and 27° spin rotators) in AGS

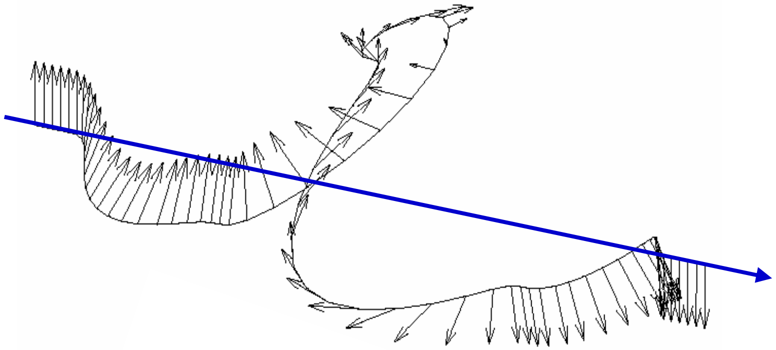
Siberian Snakes

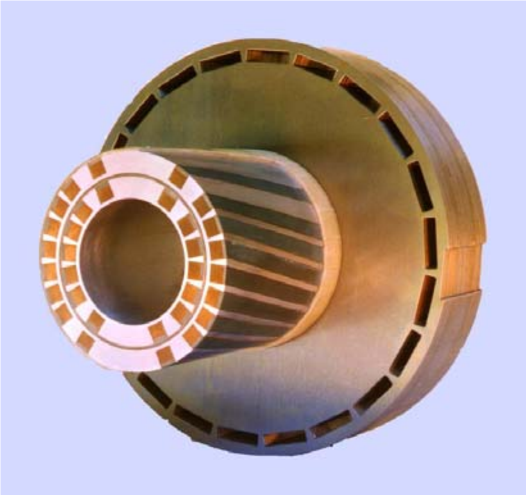




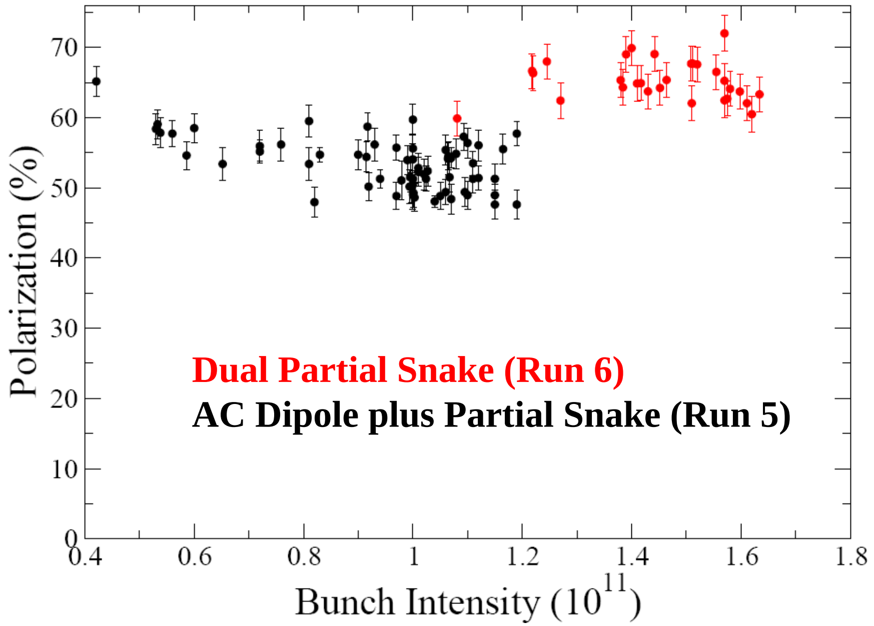
Major funding by RIKEN, Japan
RT helical dipole constructed at Tokano Ind., Japan
SC helical dipoles constructed at BNL

AGS Siberian Snakes: variable twist helical dipoles, 1.5 T (RT) and 3 T (SC), 2.6 m
RHIC Siberian Snakes: 4 SC helical dipoles, 4 T, each 2.4 m long and full 360° twist





AGS Polarization



- Dual Partial Snake in AGS avoided depolarization from all vertical depolarizing resonances and largely eliminated intensity dependence
- Tests during Run 7: eliminated ~ 5% depolarization from horizontal depolarizing resonances and identified ~10% polarization loss at low energy that depends on partial snake strength
- Plan to study low energy polarization loss and also increase acceleration rate at low energy → goal to reach 70% polarization at AGS extraction energy.

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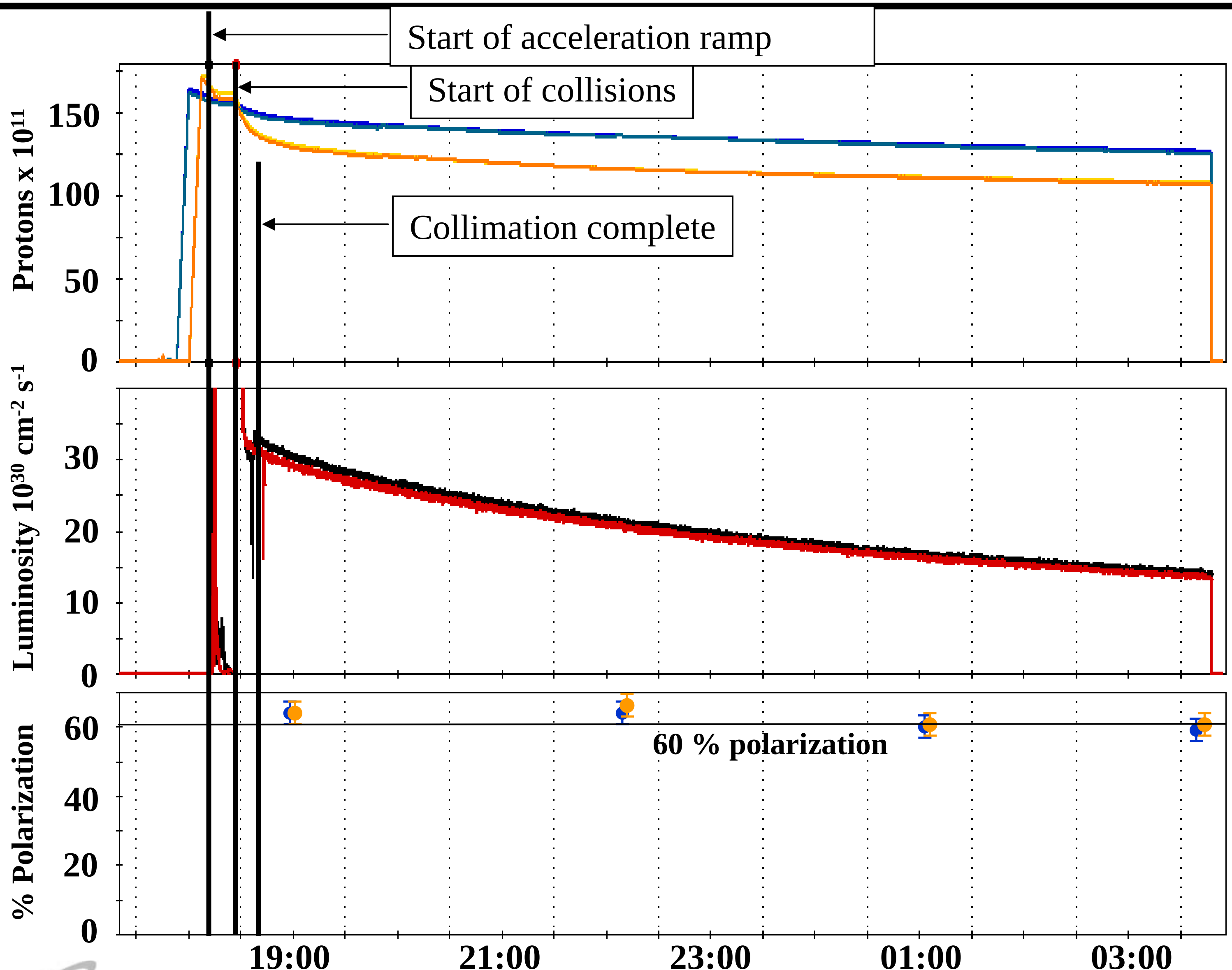
Luminosity and Polarization Lifetimes in RHIC at 100 GeV



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45 % polarization on first acceleration to 250 GeV!

Enhanced RHIC luminosity (by 2009)

Machine goals for next two years with upgrades in progress:

- **Enhanced RHIC luminosity (112 bunches, $\beta^* = 1$m):**
- **Au – Au: 8×10^{26} cm^{-2} s^{-1} (100 GeV/nucleon)**

Exceeded by 50% !

- **For protons also 2×10^{11} protons/bunch (no IBS):**
- **p↑ – p↑: 60×10^{30} cm^{-2} s^{-1}; 70 % polarization (100 GeV)**
  150×10^{30} cm^{-2} s^{-1}; 70 % polarization (250 GeV)

3 × achieved

(luminosity averaged over store delivered to each of 2 IRs)

- Exceeded Au luminosity goal
- pp luminosity improvements:
  - Correct non-linear chromaticity → reduced tune spread
  - Near integer working point → accommodate larger beam-beam tune spread
- Achieved 45% polarization at 250 GeV in first try!
  - Correct tunes and orbits at first strong intrinsic resonance to reach full polarization

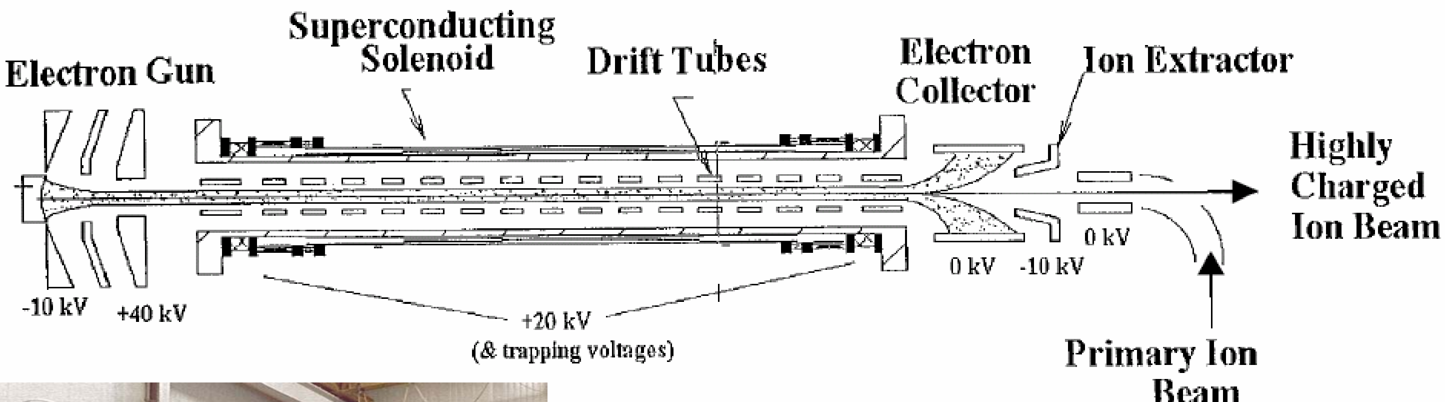
Major Upgrades

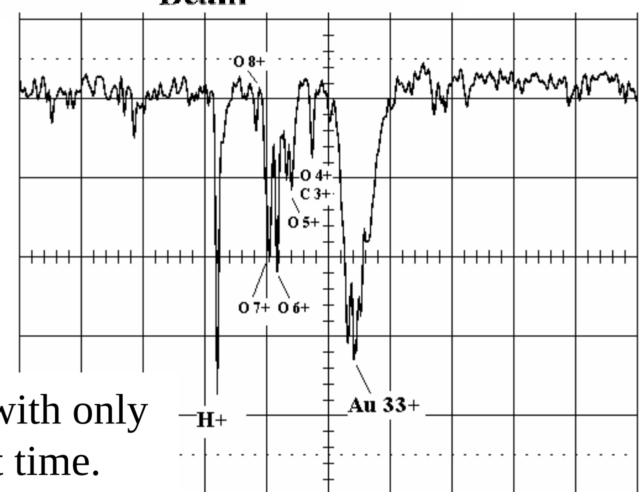
- EBIS (low maintenance linac-based pre-injector; all species incl. U and polarized ^{3}He)

- RHIC II luminosity upgrade (~ x 10 [~ 70×10^{26} cm^{-2} s^{-1}], feasibility established, ongoing R&D to reduce cost)

Electron Beam Ion Source (EBIS, ≥ 2010)

- New high brightness, high charge-state pulsed ion source, ideal as source for RHIC
- Produces beams of all ion species including noble gas ions, uranium (RHIC) and polarized He^3 (eRHIC)
- Achieved 1.7×10^9 Au^{33+} in 20 μs pulse with 8 A electron beam (60% neutralization)
- Construction schedule: FY2006 – 10





Gold charge state with only 40 ms confinement time.

RHIC II Luminosity Upgrade - Electron Cooling ($\geq$ 2013)

Objectives

- Eliminate beam blow-up from intra-beam scattering at 100 GeV
- Increase RHIC luminosity: For Au-Au at 100 GeV/A by ~10
- Cool polarized p at low energy
- Reduce background due to beam loss
- Allow smaller vertex

Challenges

- Cooling rate reduced in proportion to γ^2 or slower. (10^4 for $\gamma = 100$)
- Energy of electrons 54 MeV, well above DC accelerators, requires bunched electrons.
- Need exceptionally high electron beam brightness (high bunch charge with low emittance)

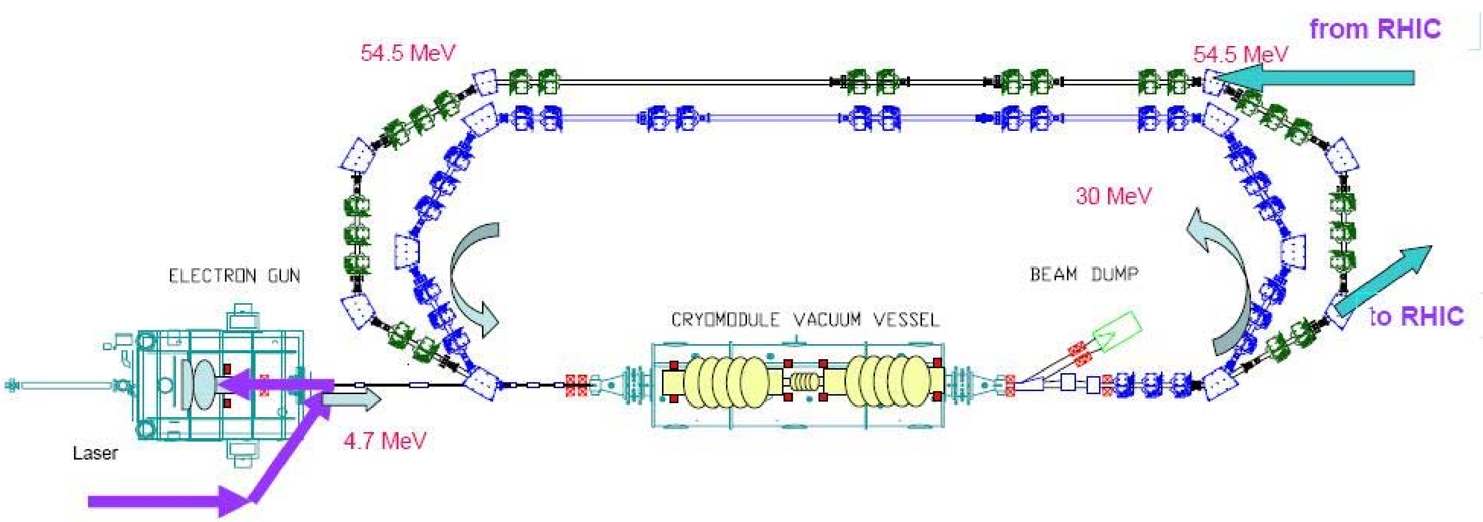
RHIC II – electron cooling

Use non-magnetized cooling (no solenoidal field)

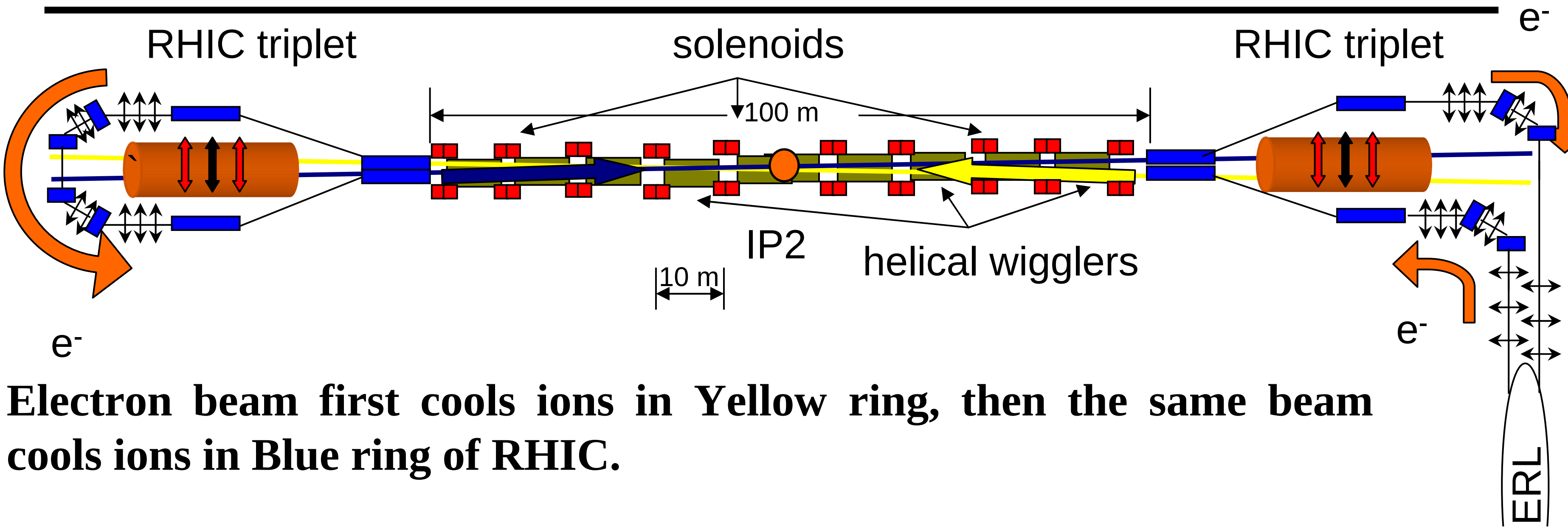
(demonstrated with 8.9 GeV antiprotons in Fermilab Recycler – Nagaitsev et al.)

For 100 GeV/nucleon Au beams need:

- 54 MeV electron beam; 5nC per bunch; rms emittance < 4 μm; rms $\Delta p/p < 5\times10^{-4}$
- 100 m cooling section



Electron cooling section in IR2



Electron beam first cools ions in Yellow ring, then the same beam cools ions in Blue ring of RHIC.

R&D issues:

- Benchmarking of IBS and cooling simulation codes (non-magnetized e-cooler at FNAL) ✓
- Development of 5 - 10 nC, 703.8 MHz CW SCRF electron gun (10 MHz rep. rate)
- Development of 703.8 MHz CW superconducting cavity for high intensity beams
- Construction of Test Energy Recovering Linac (ERL) at high electron beam current

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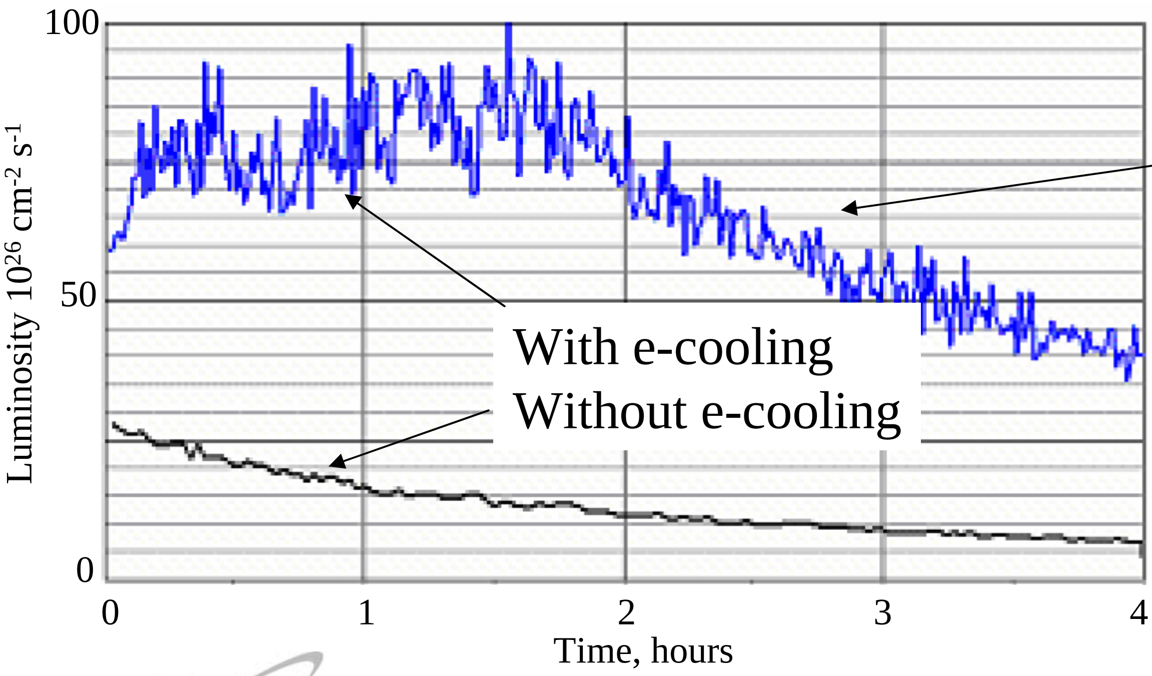
Electron Cooling Simulations

E-cooling system under development allows:

- Cooling of all species at high bunch intensities
- Cooling down to transition energy
- Pre-cooling of protons at lower energies (30 GeV)
- Limited cooling of protons at 100 GeV



Luminosity leveling through continuously adjusted cooling

Store length limited to 4 hours by "burn-off"

Four IRs with two at high luminosity

RHIC II Luminosities with Electron Cooling

Gold collisions (100 GeV/n x 100 GeV/n):	**w/o e-cooling**	**with e-cooling**
	enh. design (achieved)	
Emittance (95%) $\pi\mu m$	$15 \rightarrow 40$	$15 \rightarrow 12$
Beta function at IR [m]	1.0 (0.8)	0.5
Number of bunches	111 (103)	111
Bunch population [10^9]	1.0 (1.1)	$1.0 \rightarrow 0.5$
Beam-beam parameter per IR	0.0018	0.0018
Ave. store luminosity [10^{26} cm^{-2} s^{-1}]	8 (12)	70

Pol. Proton Collision (250 GeV x 250 GeV):		
Emittance (95%) $\pi\mu m$	20	12
Beta function at IR [m]	1.0	0.5
Number of bunches	111	111
Bunch population [10^{11}]	2	2
Beam-beam parameter per IR	0.007	0.012
Ave. store luminosity [10^{32} cm^{-2} s^{-1}]	1.5	4.0

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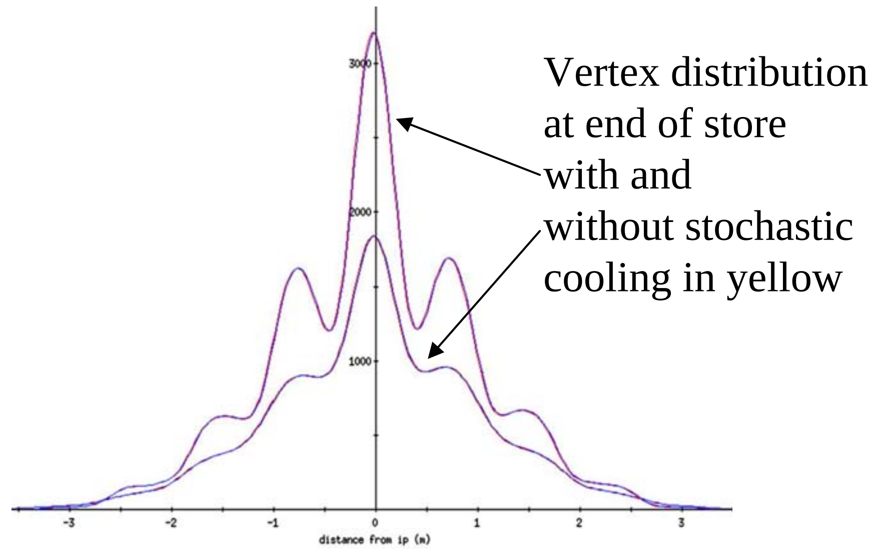
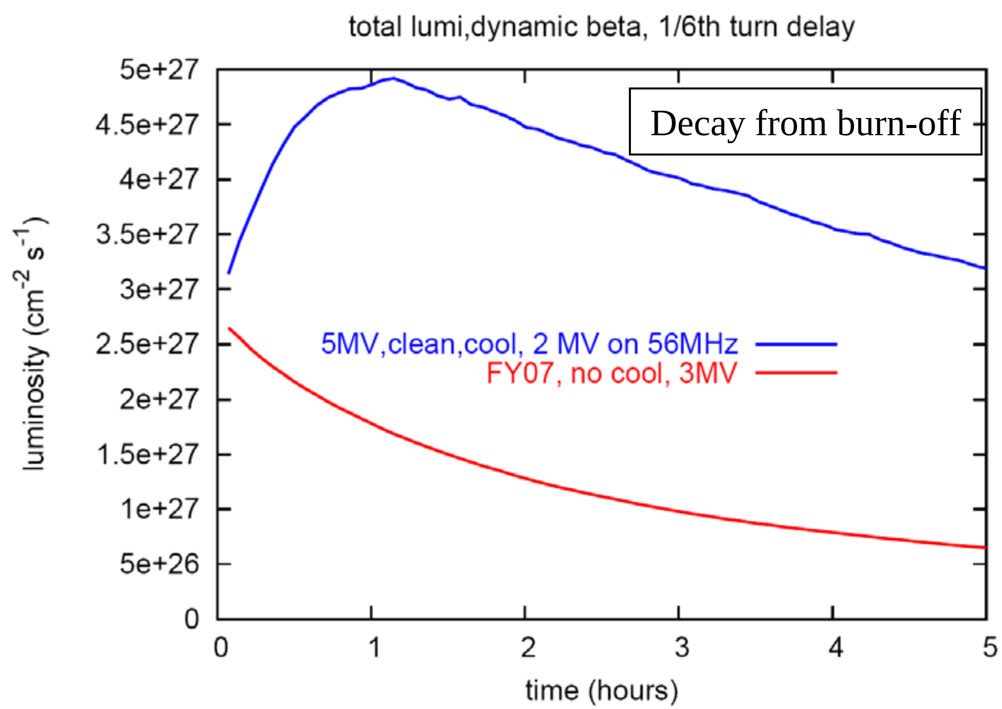
Stochastic Cooling at RHIC

- Longitudinal bunched beam stochastic cooling demonstrated at 100 GeV/n in RHIC counteracting longitudinal IBS.
- Longitudinal stochastic cooling in Blue ring under construction
- Transverse stochastic cooling in RHIC at 100 GeV/n might be possible using the same approach.
- Requires 4 planes of transverse stochastic cooling and new (56MHz?) rf system





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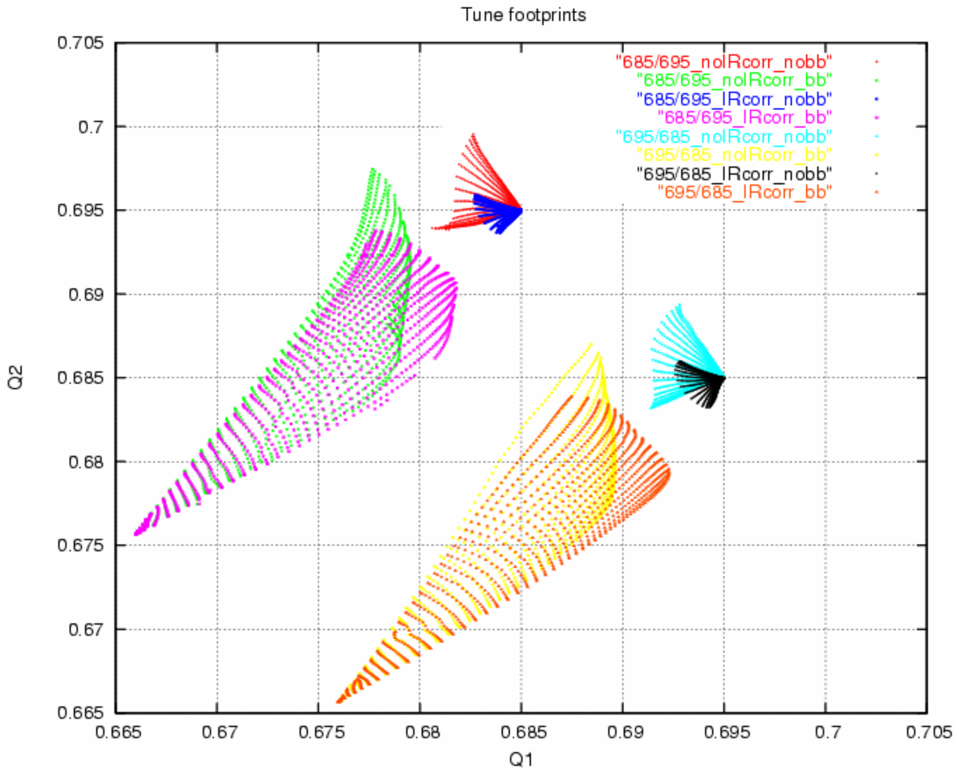
Additional Luminosity Improvements for pp Operation

- Polarized proton luminosity is limited by beam-beam tune spread
    - Use low energy electron beam to compensate head-on beam-beam interaction (x2 luminosity?)
- Polarized proton luminosity is not limited by burn-off → reduction in β* useful
    - Additional quadrupoles close to IP could reduce beta* to ~ 30 cm (x2 luminosity?)



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Summary

Since 2000 RHIC has collided, at many different collision energies,

- Heavy and light ions
- Heavy on light on ions
- Polarized protons (with up to 65 % beam polarization)

Heavy ion luminosity exceeded enhanced luminosity goal

Successful test of Au collisions at very low energy (~ ½ normal injection energy)

Successful operation of longitudinal stochastic cooling

Future runs and upgrades:

- High luminosity d-Au run
- Factor 3 increase in proton luminosity with 70 % polarization
- High luminosity 250 x 250 GeV polarized proton run
- Uranium beams from EBIS
- RHIC II luminosity upgrade (~ × 10 [~ 70 × 10^{26} cm^{-2} s^{-1}])